Accelerating the next technology revolution

Resist Technology -- Recent Progress and Future Prognosis

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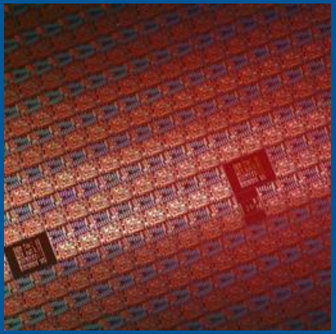
SEMATECH



Outline

- EUV resist needs
- Recent resist innovations and results
- Possible future innovations
- Shot noise issues
- Conclusions

General Resist Needs

- Absorb the right amount of actinic light
- Provide enough process resistance (etch, implant, plating . . .)
- Provide sufficient resolution
- Provide sufficient photospeed
- Improve on aerial image contrast and provide clean, reasonable smooth resist images

These needs drive new materials for every new wavelength

EUV Resist Needs

- *Absorb the right amount of actinic light*
  - EUV tools place a premium on resist photospeed
  - Film absorbance of 43.5% give maximum photospeed, but often unusable sidewall angles.
  - Film absorbance of 22% is considered a good compromise for high photospeed

Film Thickness	43.5% Absorbed A+B	22% Absorbed A+B
20.00nm	28.5	14.4
30.00nm	19.0	9.6
50.00nm	11.4	5.8
100.00nm	5.7	2.9
200.00nm	2.8	1.4
500.00nm	1.1	0.6

Current typical resist thickness for EUV resists

Expect will need A+B between 7 and 15 per um for HVM EUV

Expected typical resist thickness for EUV resists in HVM

How different materials absorb at EUV

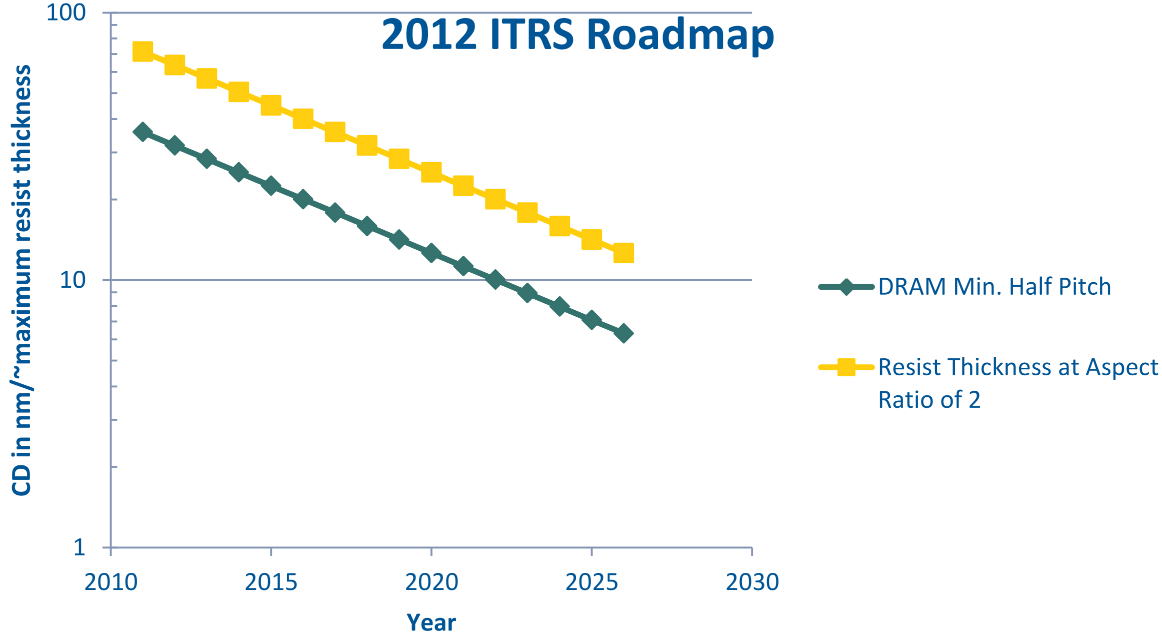
Material	A+B
Poly Styrene	2.8
PMMA	5.2
PF PMMA	17.7
Pure HfO_2	31.3
Pure ZrO_2	13.8
FEVS P1101 (2008)	3.9
2012 Leading Edge EUV CH Resist	5.2

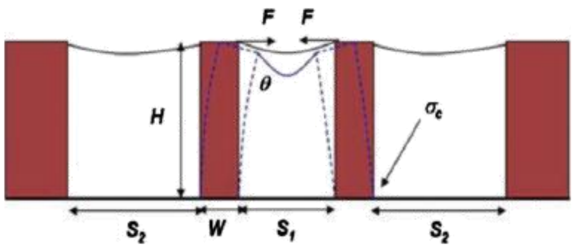
Significant progress but need more

- FEVS P1101 was IMEC POR EUV resist in 2008. See Gronheid et al.
- HfO2 nanoparticle films for ArF use are 30 to 200nm with absorbance of 0.5 to 5. (M. Trikeritos et al., Proc. SPIE, **7639** (2010)
- 2012 leading data is average of 13 contact holes resist tested at SEMATECH

EUV Resist Needs

Provide enough process resistance (etch, implant, plating . . .)





Key issue will be getting enough etch resistance from resist, even assuming trilayer stacks

Thickness of resist

Chemistry of resist

EUV Resist Needs

- *Provide sufficient resolution, photospeed, and improvement on aerial image contrast*

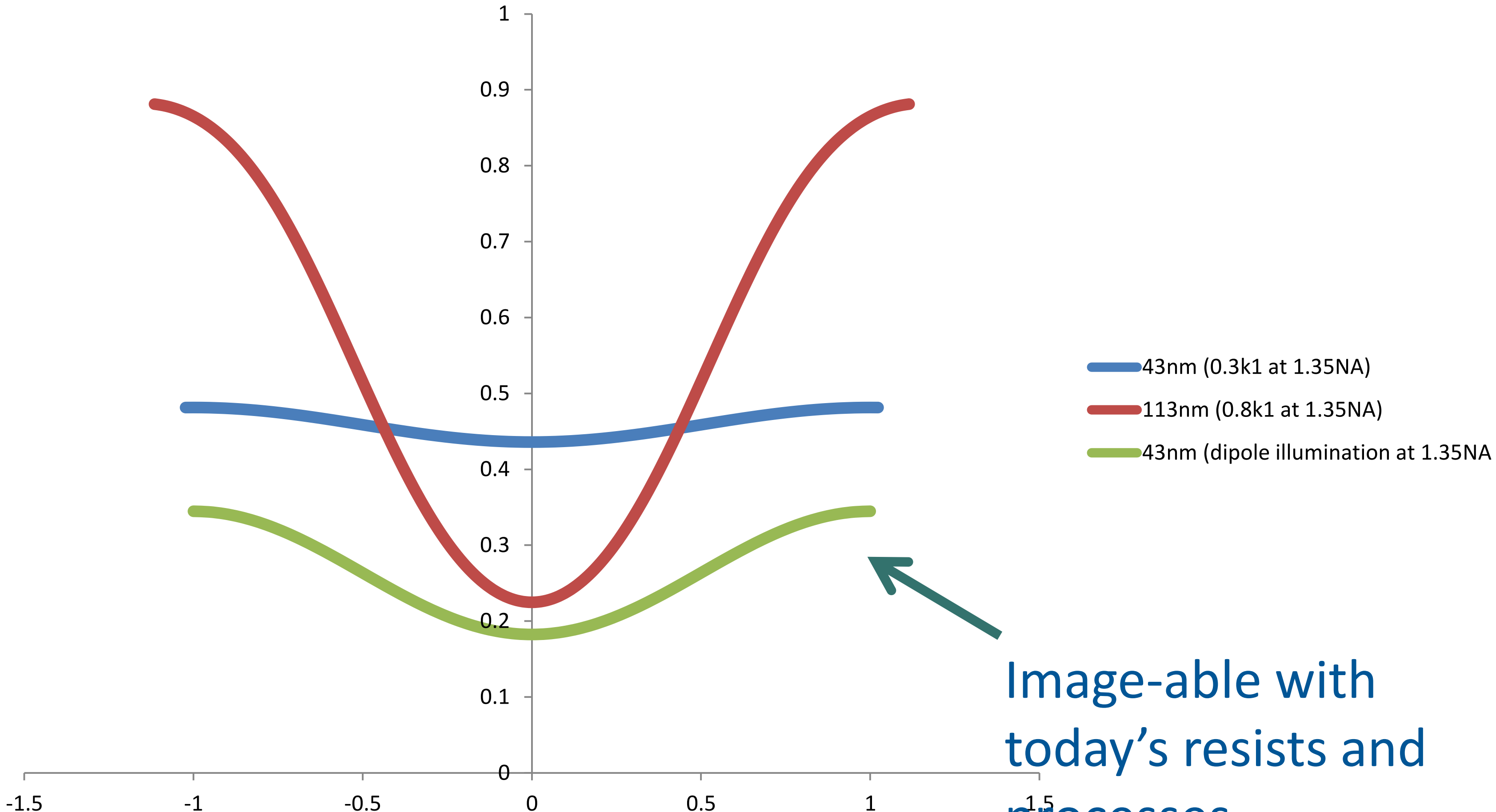
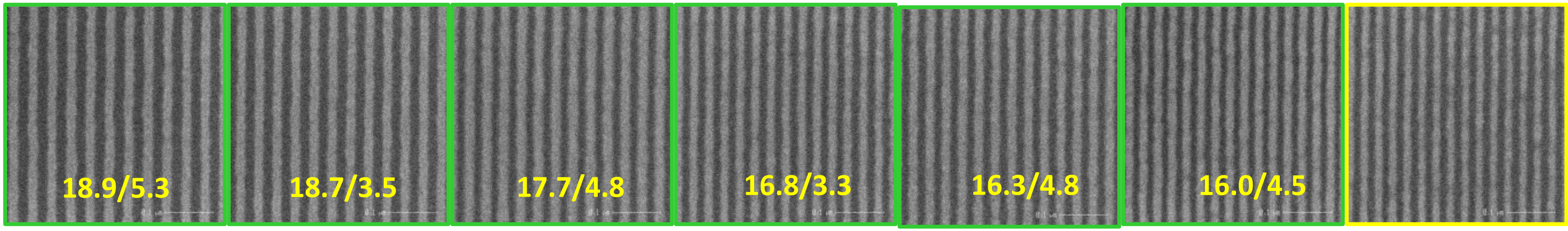


Image-able with today's resists and processes

- Chemically amplified resist systems can provide sufficient resolution at 193nm

Recent EUV Imaging Results



20nm hp	19nm hp	18nm hp	17nm hp	16nm hp	15nm hp	14nm hp
(k_1 = 0.44)	(k_1 = 0.42)	(k_1 = 0.40)	(k_1 = 0.38)	(k_1 = 0.36)	(k_1 = 0.33)	

- The resist was exposed using Berkeley EUV micro exposure tool
  - Yellow numbers show measured CD and line width roughness (LWR)
  - Excellent aerial image, but aberrations probably not up to production tool standards

- Improvement is needed, but this resolution shows capability of chemically amplified technology to meet EUV resolution needs

Key issue will be getting low enough LWR

Recent Resist Innovations

- Absorb the right amount of actinic light

High absorbance materials for EUV resists and underlayers, resist chemistry that doesn't outgas, out of band insensitive PAGs

- Provide enough process resistance (etch, implant, plating . . .)

New rinses and developers that enable thicker resist film without line collapse, new spin on hard mask materials,

- Provide sufficient resolution

Negative tone developable resists enable use of better aerial images, polymer bound PAG and other approaches to low diffusion resists, shrink materials for smaller CDs

- Provide sufficient photospeed

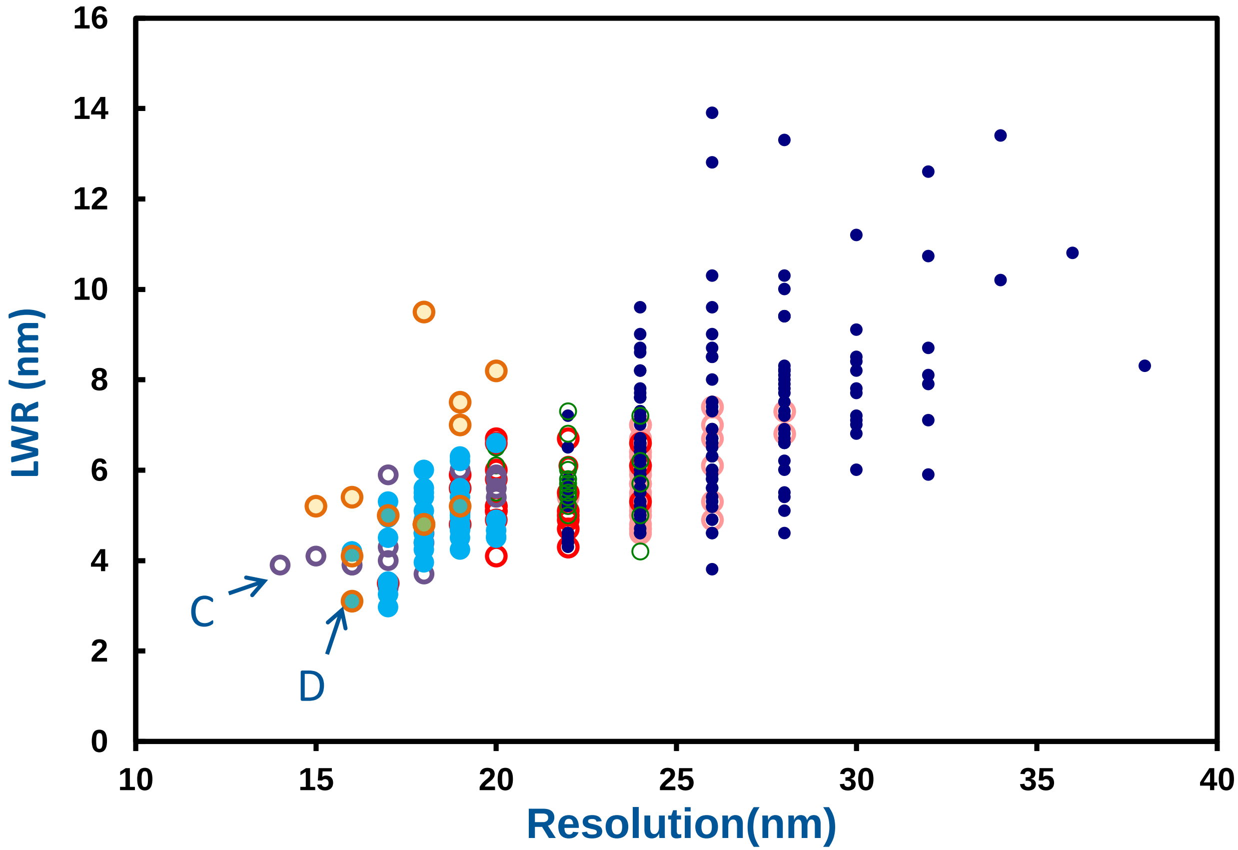
Resist post processing enabling lower LWR and usability of faster resists, immersion resists with self forming top coats for improved scanner throughput, scanner and mask bias optimization for throughput

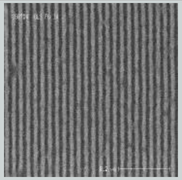
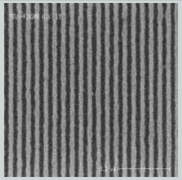
- Improve on aerial image contrast and provide clean, reasonable smooth resist images

Photodecomposable bases, resists for double patterning, EUV top coats

EUV Resist Performance Status

Resolution is meeting needs

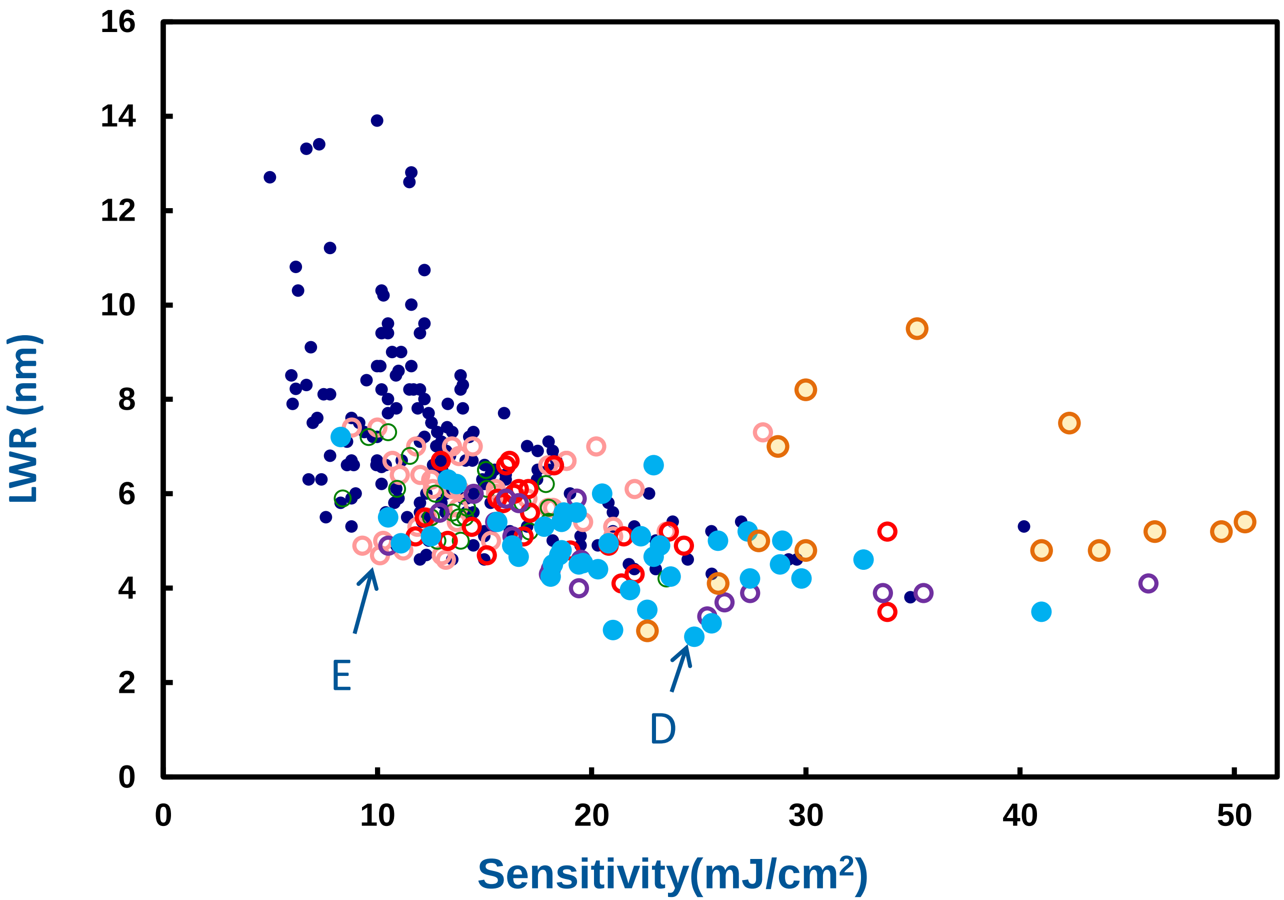


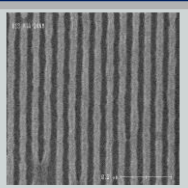
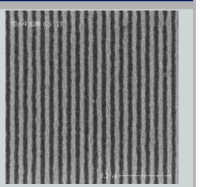
	C	D
Image		
Size	14nm HP	17nm HP
LWR	3.8nm	2.9nm
Speed	33.6mJ/cm^2	26.5mJc/m^2

Results shown are from three years of SEMATECH EUV resist benchmarking

EUV Resist Performance Status

LWR vs. Sensitivity doesn't meet EUV needs

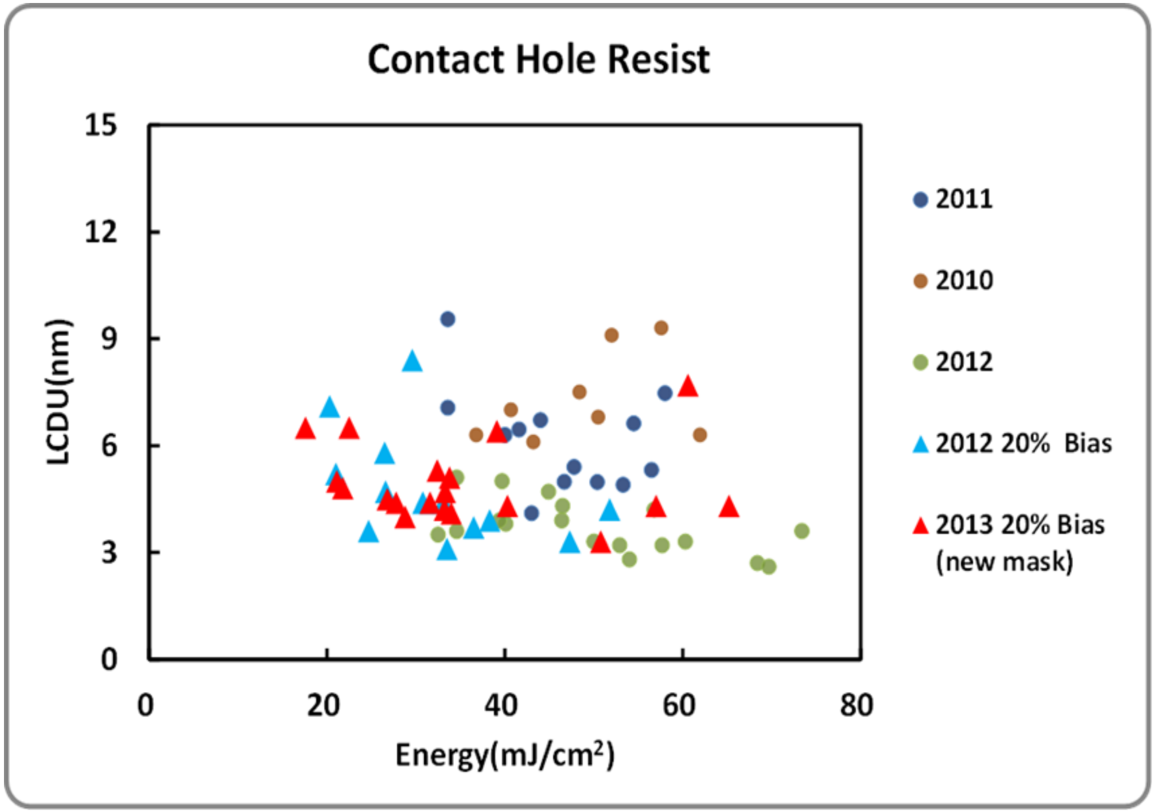


	E	D
Image		
Size	24nm HP	17nm HP
LWR	4.7nm	2.9nm
Speed	10.1mJ/cm^2	26.5mJc/m^2

Results shown are from three years of SEMATECH EUV resist benchmarking

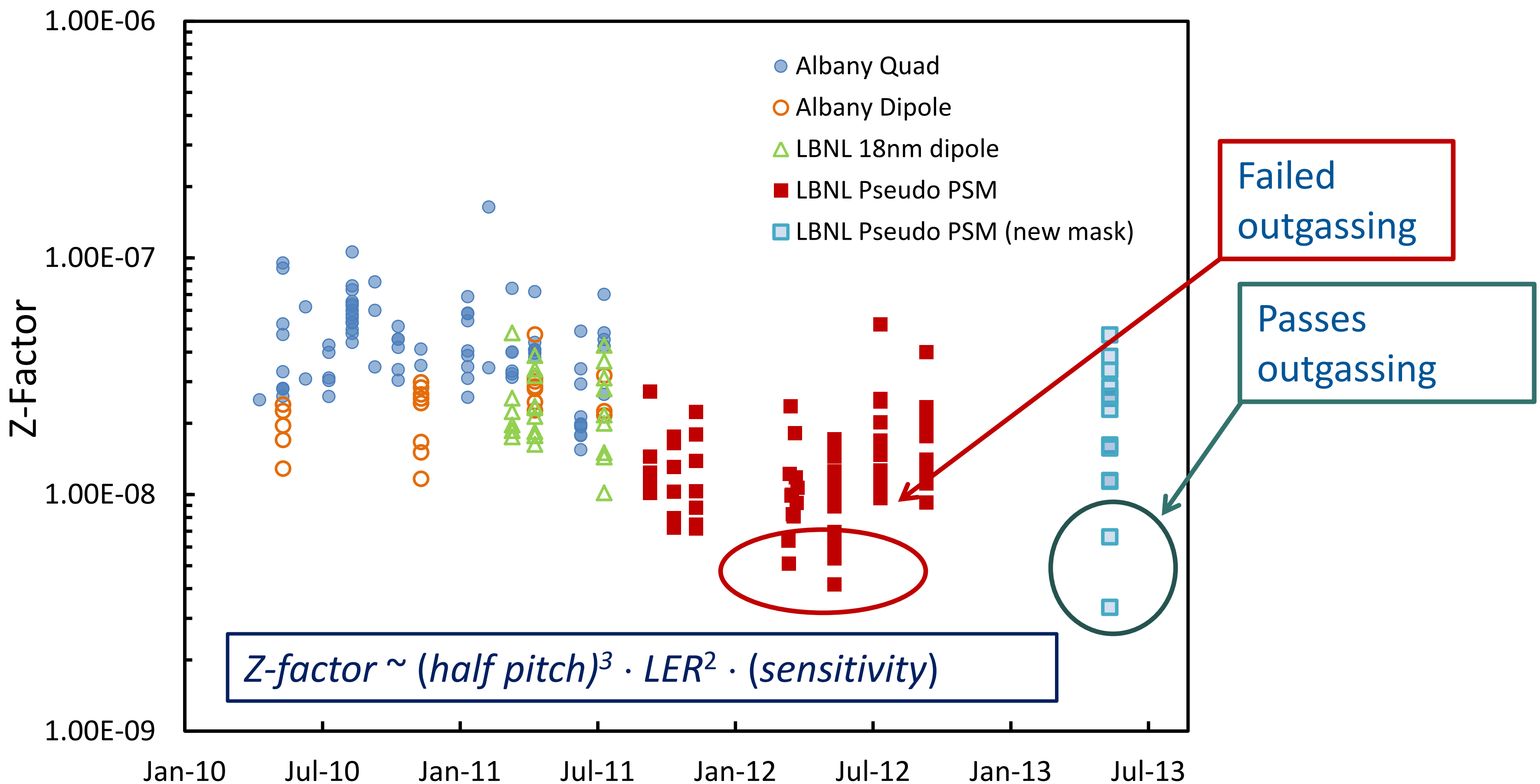
EUV Resist Performance Status

CDU vs. Sensitivity doesn't meet EUV needs



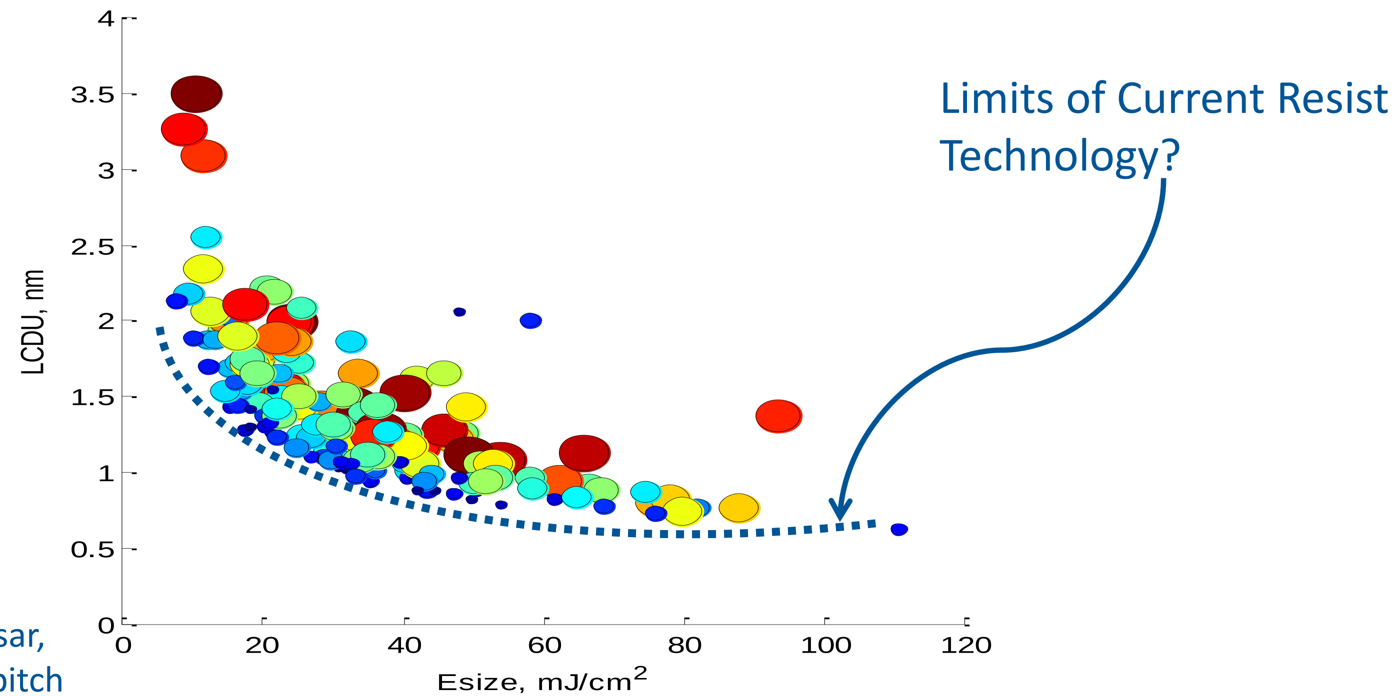
- Expected trend observed that fast resists have more CDU than slower ones (similar to LWR, photospeed trend for lines and spaces)
- But a lot of variation among fast resists in observed CDU
  - Not explained by different absorbances or exposure latitudes

Z-Factor of EUV Resists Improves Over Time



- Data represents materials from six suppliers
- A better aerial image clearly gives a lower Z value
- There is improvement over time

Simulation of EUV resists with varied parameters

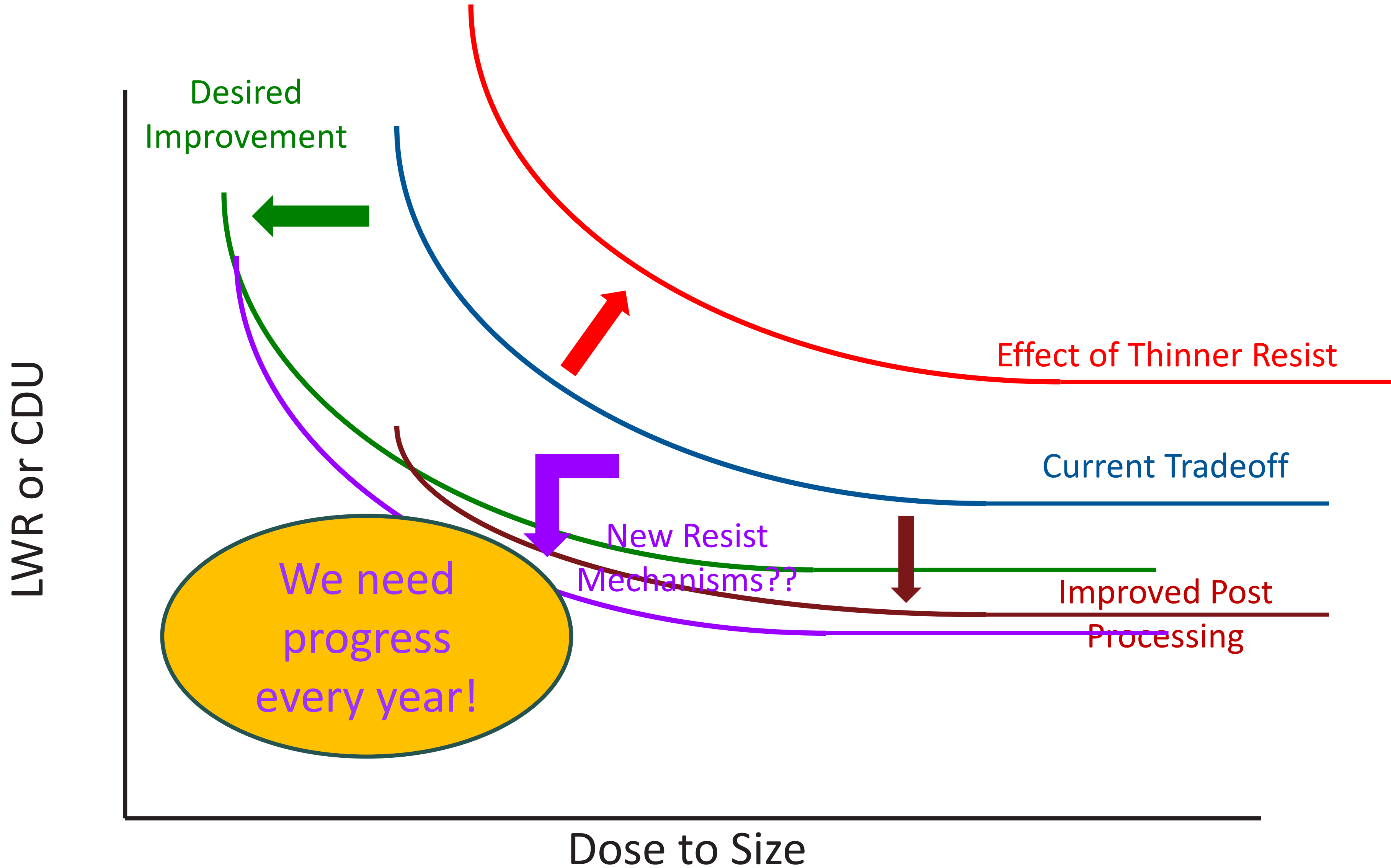


0.25 NA, 0.51/0.81 quasar, 28 nm holes on 56 nm pitch

- Marker show performance of randomized stochastic resist formulations
- Size and color of markers indicates acid diffusion rate (nm2/s)
- Simulations suggest lowering acid diffusivity rate benefits exposure latitude and LCDU

Figure is from Sarma et al., “Simulation-assisted layout biasing in EUV lithography and prediction of an optimum resist parameter space", in Extreme Ultraviolet (EUV) Lithography IV, Proceedings of SPIE Vol. 8679

Desired Improvements in Resist Performance



Possible future resist Innovations

- Absorb the right amount of actinic light

Further improvements in absorbance, metal based resists, higher aspect ratio imaging

- Provide enough process resistance (etch, implant, plating . . .)

Metal based resists, cross linked resists for better resistance to pattern collapse

- Provide sufficient resolution

Resists with lower chemical blur, Negative tone developable resists for EUV, EUV resists for double patterning, resists with novel mechanisms

- Provide sufficient photospeed

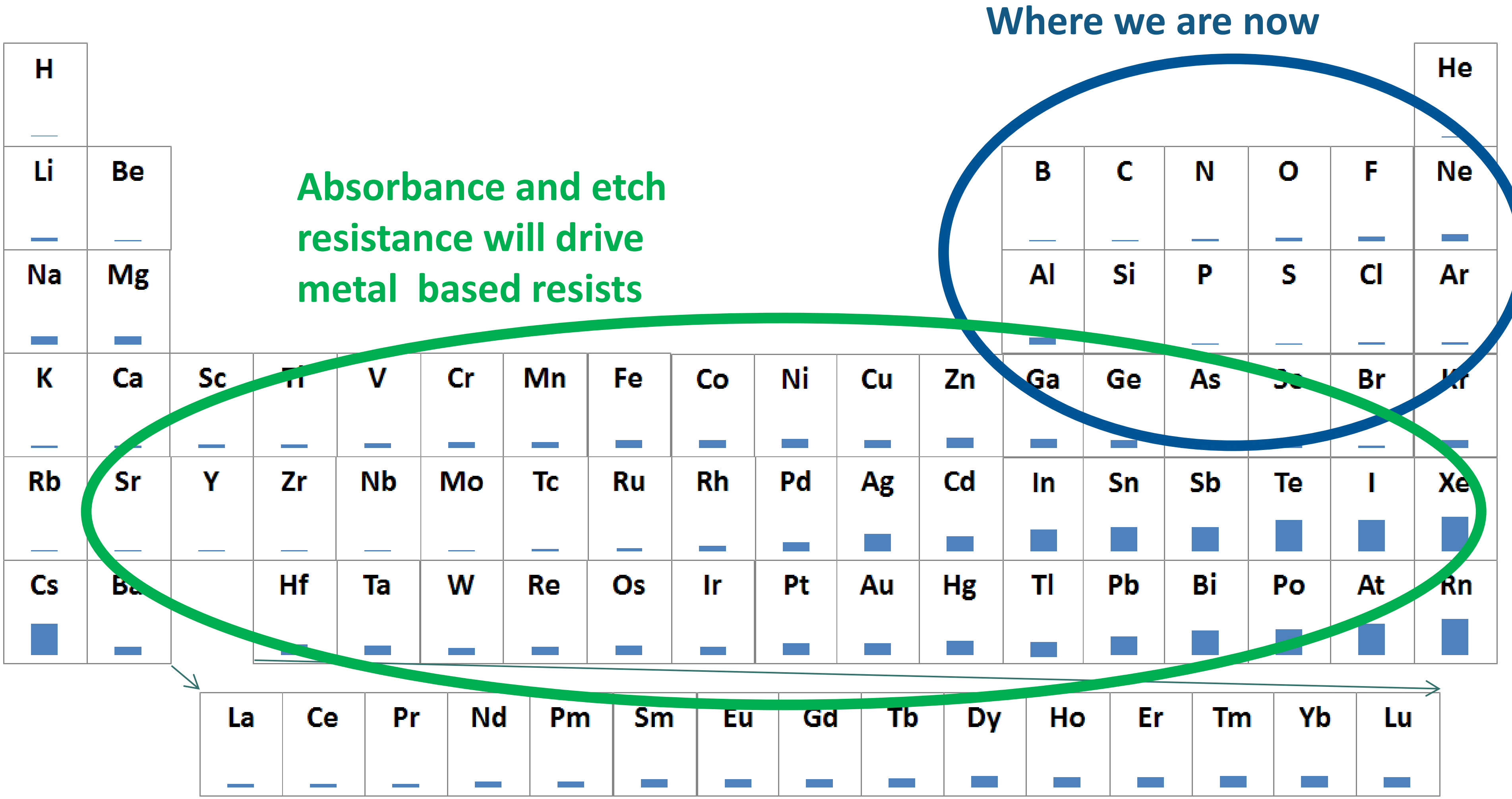
New mechanisms for solubility switching, Improved use of secondary electrons

- Improve on aerial image contrast and provide clean, reasonable smooth resist images

Designs to accommodate LWR/CDU. Post processing to improve LWR and CDU, non chemically amplified materials with high photospeed

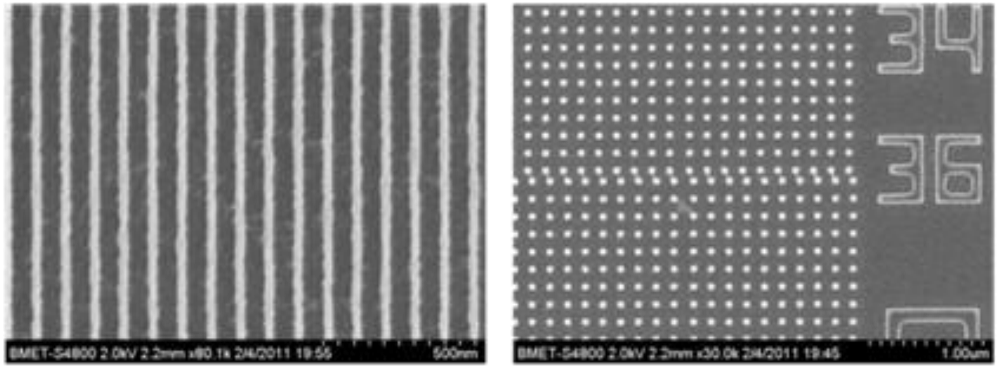
There is always room for and there always will be more ideas

Periodic Table of Absorption at 13.5nm



Recent Hafnium Resists show promise

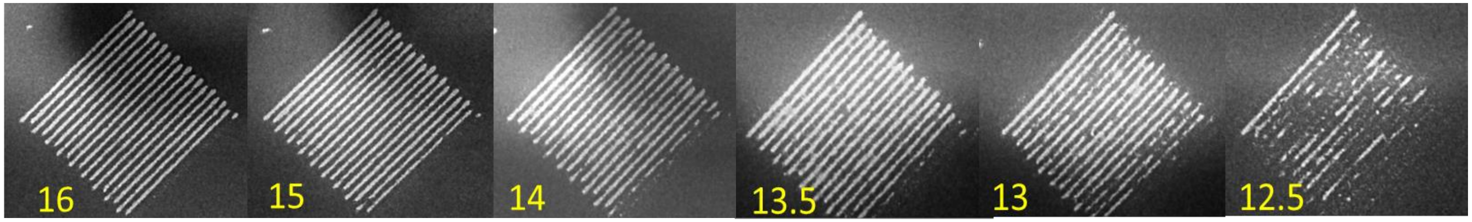
- 39 nm thin film
- 25 nm lines, 1:2 L/S ratio
- 36 and 34 nm posts
- Dose = 6.6 mJ/cm^2



See M. Krysak et al., “Development of an inorganic nanoparticle photoresist for EUV, e-beam, and 193nm lithography,” Proc. SPIE Microlithography 7972 (2011) and J. Stowers et al., “Directly patterned inorganic hardmask for EUV lithography,” Proc. SPIE Microlithography 7972 (2011)

Recent Hafnium Resists show promise (Work from Inpria)

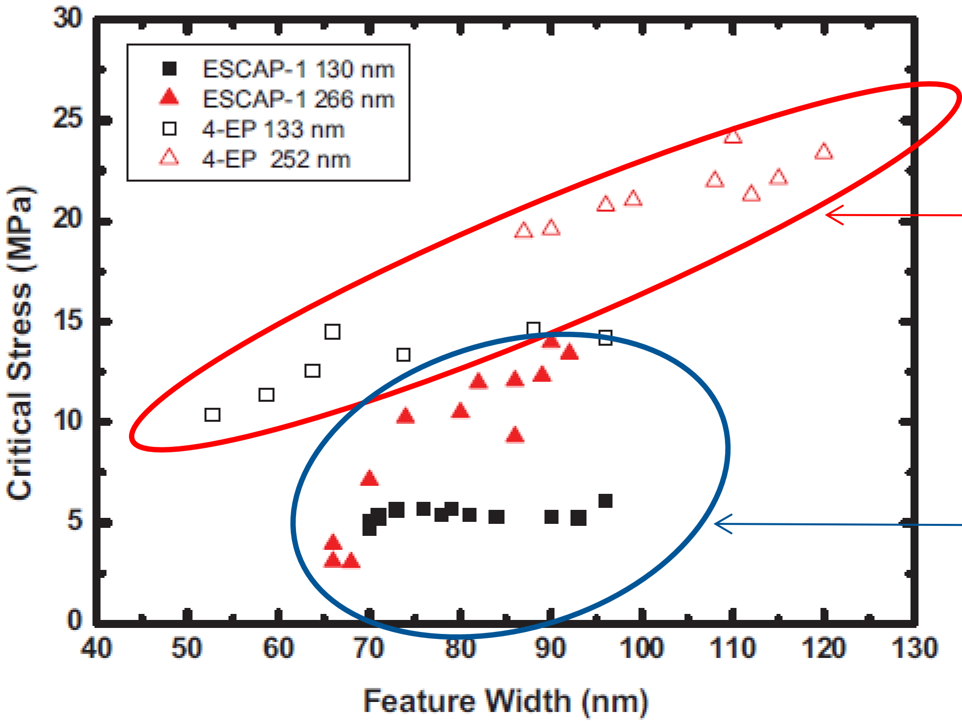
- 16 nm hp resolution / 2.8 nm LWR with modulation down to 12 nm hp



- Photo sensitivity needs to improve (70 mJ/cm2)

Improved Pattern Collapse with cross linked resists

- The higher modulus of the negative tone cross-linked resist leads to improved pattern collapse performance in negative tone resists due to higher critical stress before collapse (Henderson et al., JVST B 28, C6S6, 2010)



Cross linked negative tone resist

Classis chemically amplified positive tone resist

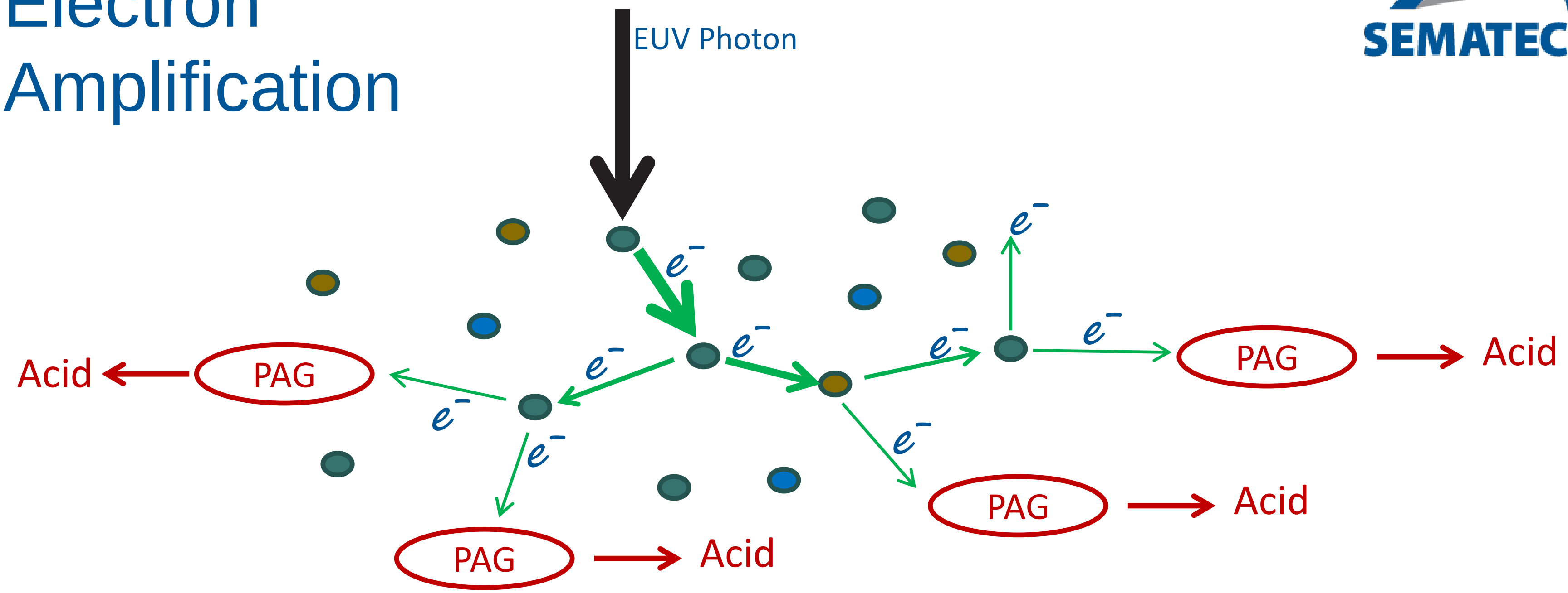
New Mechanisms for Solubility Switches

- Solubility switches that don't need acid --- Possible example:

- Solubility switches that do more chemistry per acid --- Possible example:

- A key question is will a novel chemical switching mechanisms for resists improve the photospeed, LWR, resolution tradeoff?

Electron Amplification



- The polymer matrix of the resist is a key component for capturing photons and making them useful
- Each EUV photon generates a cascade of electrons
  - More than one electron generated per photon
  - More than one of these electrons can generate acid
- Typical EUV quantum yields of acid
  - Three acids per photon in a typical resists
  - Values as high as six acids per photon have been reported

Better Use of Secondary Electrons

- More acids per photon
- Control of spatial distribution of electrons
- Electron capture materials?

Example of Post Processing of Lines and Spaces

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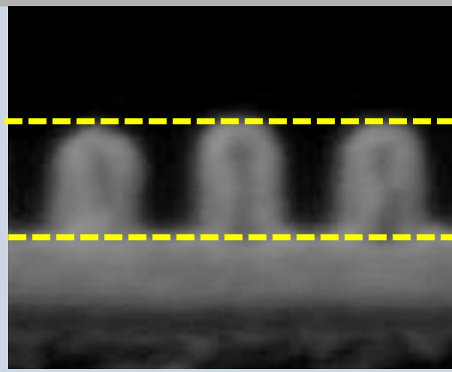
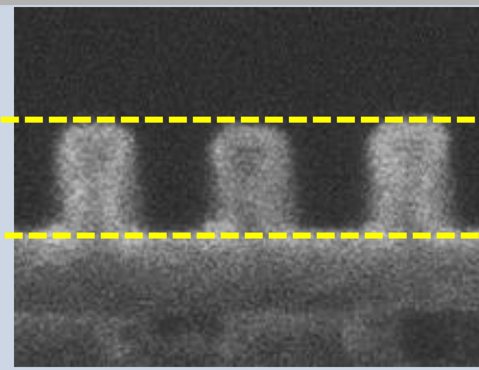
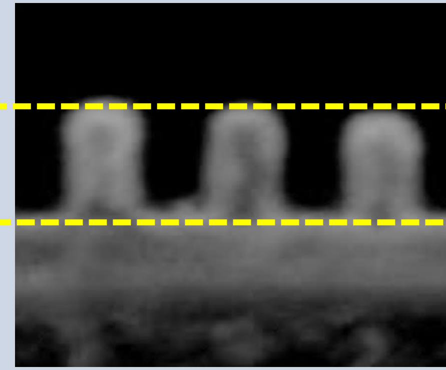
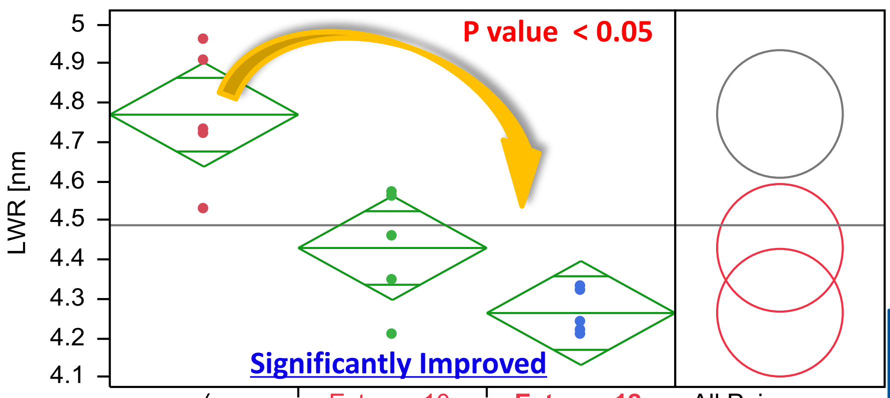
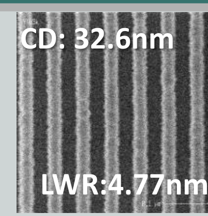
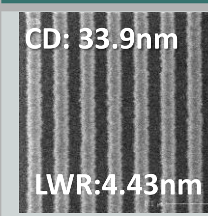
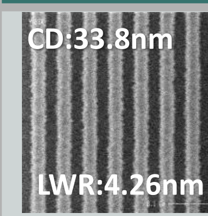
	w/o FIRM	w/ Extreme10	w/ Extreme12
X-section			



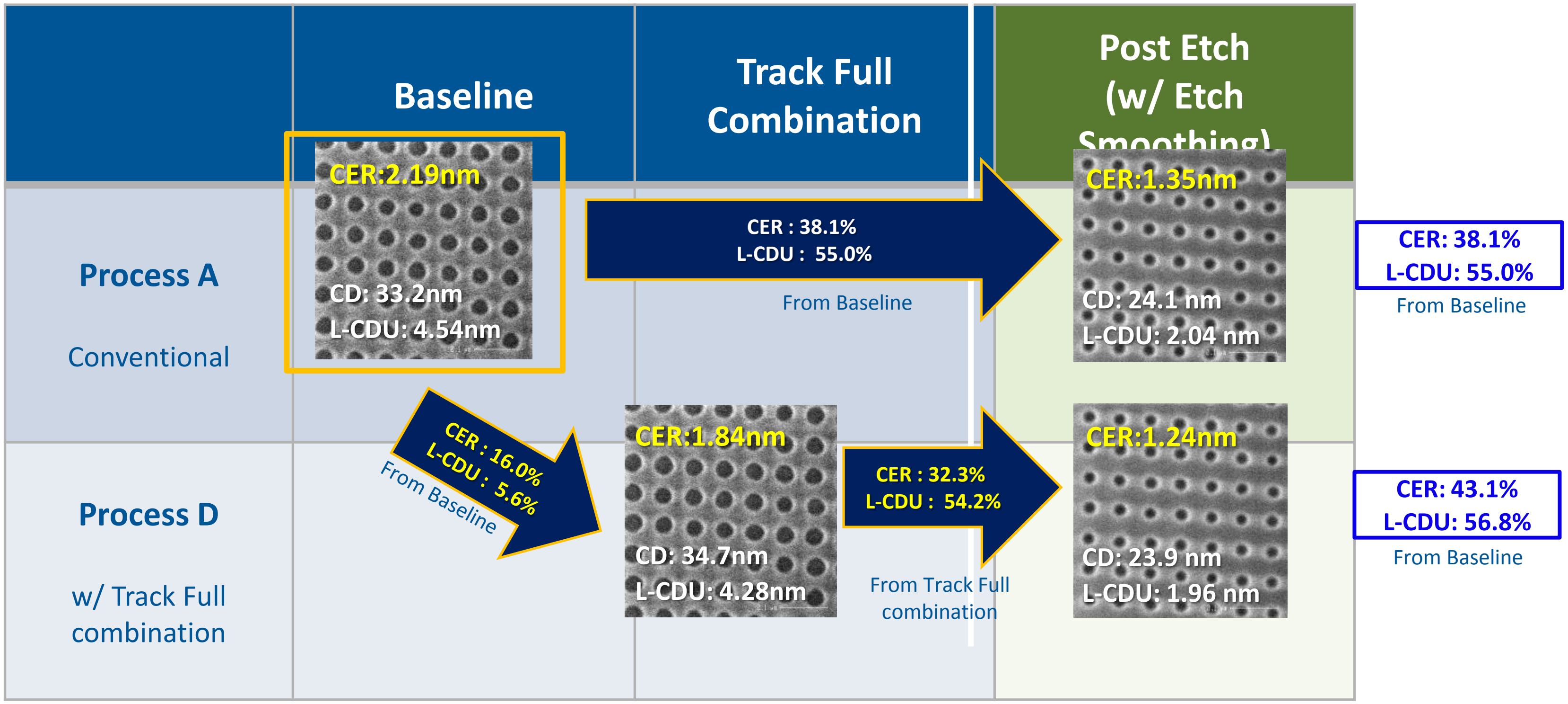
	w/o FIRM	w/ Extreme10	w/ Extreme12
Top-Down Image			

Exposure: EUV Alpha Demo Tool, Mask CD: 32nm,
Resist: Resist G, Resist thickness: 80nm

FIRM Extreme series improves 32nm L/S LWR by 7% without changing the resist thickness or profile

- Data from K. Petrillo, KY Cho, C. Montgomery, A. Friz, D. Ashworth, M. Neisser, S. Wurn, T. Saito, L. Huli. A. Ho, A. Metz, “Resist Process Applications to Improve EUV Patterning,” Procedings SPIE, 2013

Example of Post Processing of Contact Holes



- Post etch result shows CER can be improved over **38%** by Etch based smoothing techniques
- With track full combination process achieve around **43%** CER reduction
- **55%** improvement in L-CDU with etch based techniques

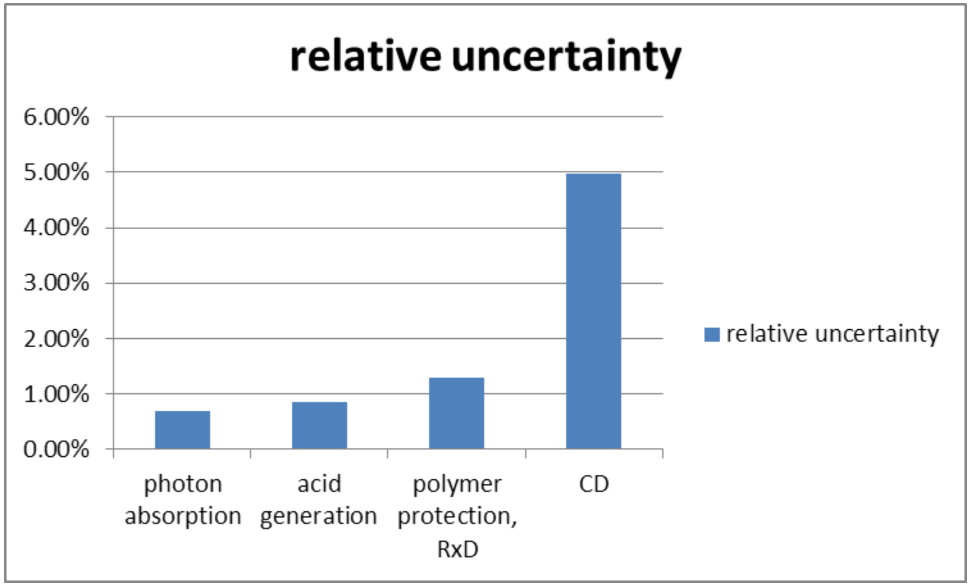
- Data from K. Petrillo, KY Cho, C. Montgomery, A. Friz, D. Ashworth, M. Neisser, S. Wurn, T. Saito, L. Huli. A. Ho, A. Metz, “Resist Process Applications to Improve EUV Patterning,” Procedings SPIE, 2013

Photon Shot Noise Simulation

Photons per Pixel		
0.001	0.01	0.1
1	10	100
1000	10,000	100,000

http://en.wikipedia.org/wiki/File:Photon-noise.jpg

Simulation of Source of Variation



	photons	Acid	Polymer prot.	CD
Relative uncertainty	0.70%	0.85%	1.28%	4.98%
Standard deviation	145	266	0.010	1.3nm
Mean	20,817	31,296	0.740	26.0

- Calibrated resist model with 60nm film thickness
- Exposure conditions same as for data reported in this paper
- Graph shows 1σ variation as percent of average value
- Counts shown are for a 31nm x 31nm x 60nm tall volume centered on one contact hole

- Our thanks to J. Biafore and KLA-Tencor for the simulations of relative uncertainty

C/H Variance Distribution
(compared to 10% of CD ITRS 2012 roadmap requirement)

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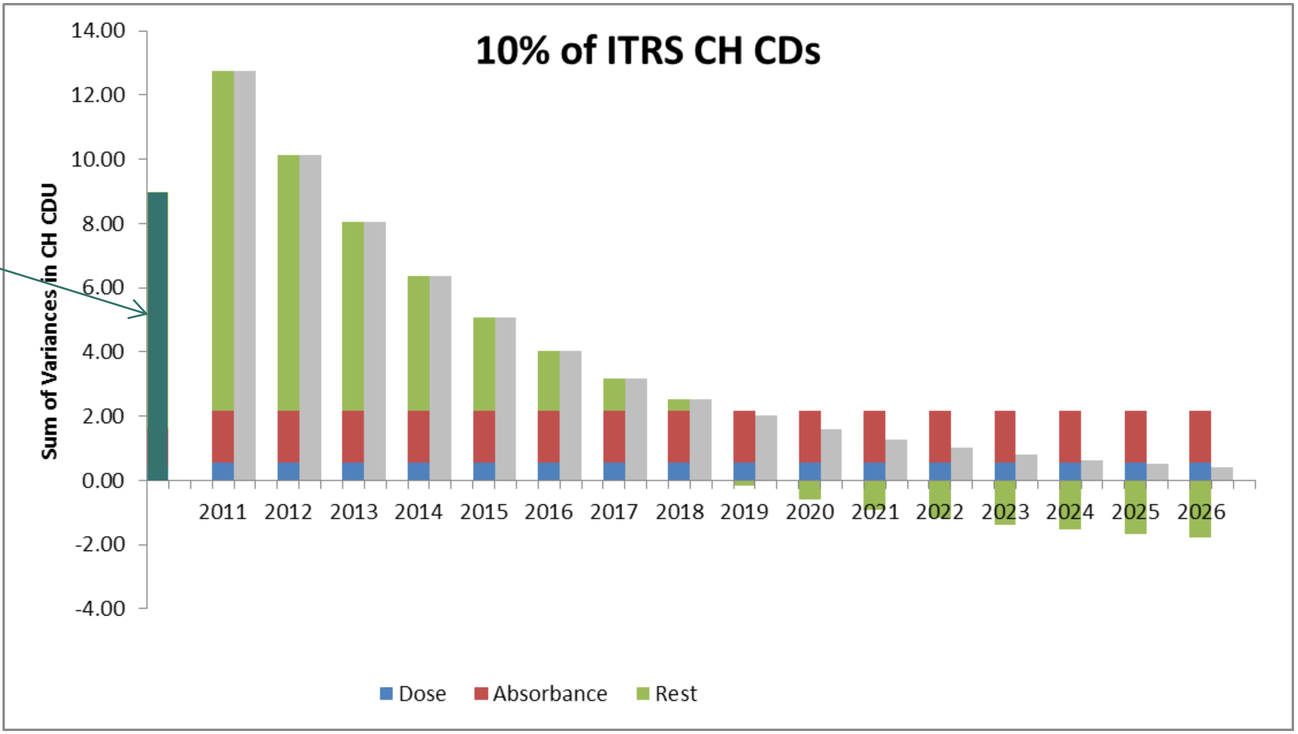
Current leading edge resist performance



- The blue and red bars together show calculated shot noise
- The green segment shows what is left for resist stochastics, including variations in acids generated per photon and in deprotections per acid
- Green bars are negative if the resist or process has to improve the CDU over calculated shot noise variation
- Calculations assume constant exposure latitude of 12%, a film absorbance of 25%, a mask bias of +20% and a dose to size of 15mJ/cm^2

How Can the Industry Accommodate Shot Noise?

- Make resists with high absorbance that have chemistry giving relatively low CDU or LWR
  - We need to understand observed resist to resist differences and learn how to consistently get lower CDU and/or LWR
- Use slower photoresists to reduce the photon shot noise component of CDU and LWR
- Post processing to reduce CDU and LWR
  - Work on this has been reported. Etch, smoothing and other processes have potential
- Use of designs that accommodate contact hole CDU or line LWR
  - For example, self aligned contact holes
  - Designs with intrinsically more latitude in CD size
  - Such designs may have a cost in circuit area or in process complexity

Conclusions

- Resist is meeting current targets for resolution and is close in photospeed thanks to many innovations and progress in resist chemistry and processing
- There are promising avenues for further improvement of resist that are now in the research stage
- LWR and CDU will continue to be a problem that needs to be mitigated or managed. Post processing is likely to be needed to meet requirements. Longer term, slower resists may be more optimal as EUV power sources improve

Acknowledgement

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